Yöneylem Araştırması ve Endüstri Mühendisliği
31. Ulusal Kongresi

Supply Chain Optimization with Environmental Conscious

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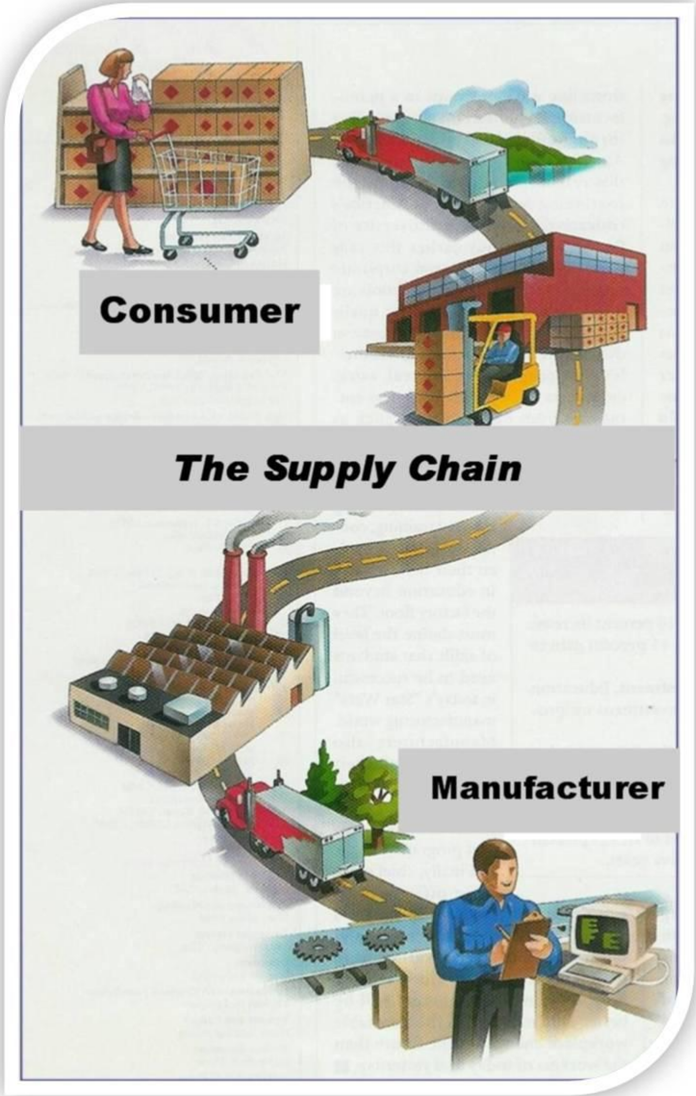
Outline

Supply Chain

Supply Chain is a set of activities

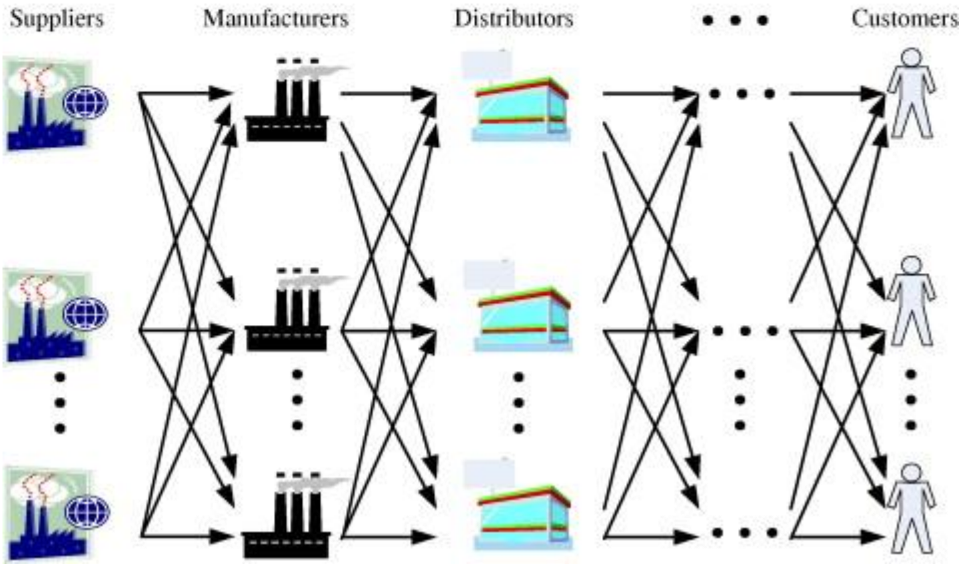
- purchasing,
- manufacturing,
- logistics,
- distribution,
- marketing

that perform the function of delivering value to end customer



Supply Chain Optimization

is determining positions and
count of actors,
amount of product flow between and
decreasing transportation costs are
handled as network design problem in
supply chain management

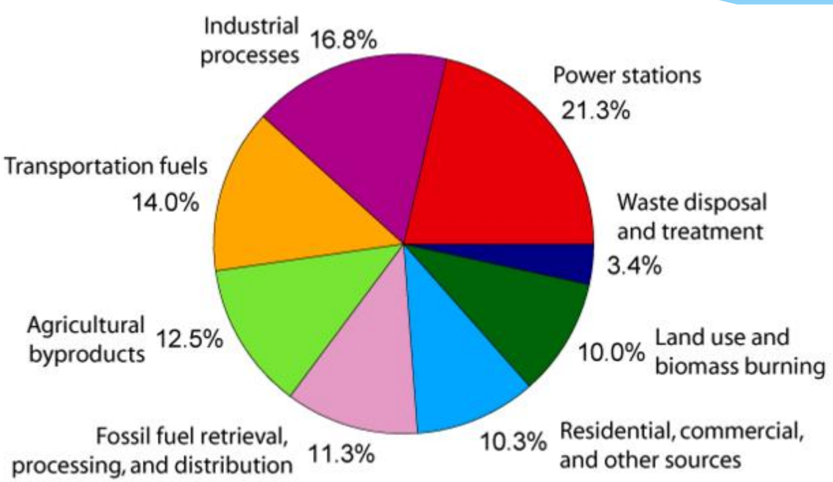


Greenness in Supply Chain

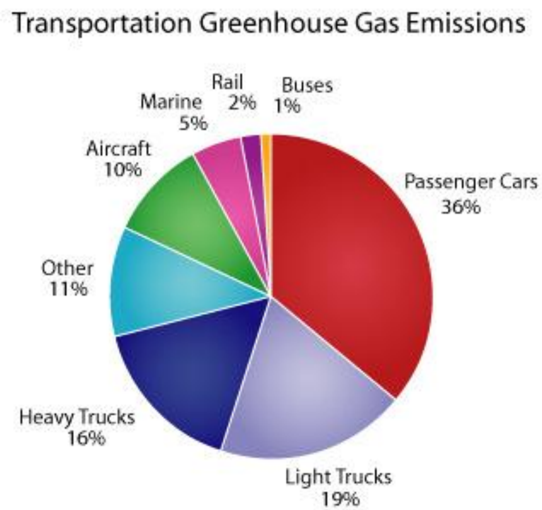
The green supply chain extends this definition by including:

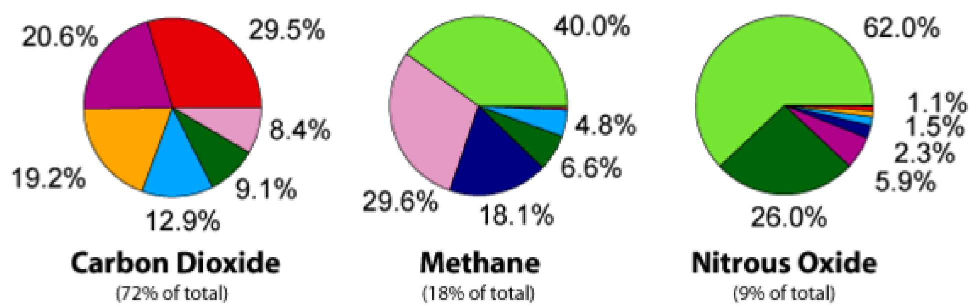
(i) Waste of all processes,
(ii) Using efficient energy resources,
(iii) Greenhouse gas emissions,
(iv) Using capacities and resources efficiently,
(v) Considering legal environmental factors

Why Go Green in Freight Transport?



Greenhouse gas emissions by sectors





The greenhouse gas emission distribution

What is being done for ‘green transportation’?

- The literature is already quite rich on freight distribution planning problems,
- The goal is usually to minimize “internal” operational costs,
- An explicit consideration of “external” (environmental) costs is essential.
- This is the motivation behind this talk.

Literature

* The literature on the supply chain network design problem and its variants is rich and the reader is referred to the book of **Geunes and Pardalos (2005)** and to the comprehensive survey by **Mula et al. (2010)** for a recent coverage of the state of the art on models and solution algorithms.

* It has been pointed out that there is a wide gap for reducing CO_2 emissions, increasing fuel efficiency, decreasing noise levels, considering roughness by extending traditional supply chain objectives to account for wider environmental and social impacts rather than just the economic costs.

Literature

* **Beamon (1999)** describe green supply chain first,

* In parallel, external and internal costs of transportation are studied by **Forkenbrock (1999, 2001)**. They estimate four general types of external costs for a ton-mile of freight shipped by truck: accidents; emissions; noise; and unrecovered costs associated with the provision, operation, and maintenance of public facilities,

* **Anciaux and Yuan (2007)** construct an intermodal (truck, train and ship) optimization model to minimize the total transportation costs for delivering goods from the Peugeot factory in Paris to Marseille. The model includes a term that quantifies the total air emissions from pollutants (CO_2, NO_x, SO_2, hydrocarbons, and dust) during product shipment,

Literature

* **Palmer (2007)** in PhD dissertation presents an integrated routing and emissions model for freight vehicles and investigates the role of speed in reducing CO_2 emissions under various congestion scenarios and time window settings.

* **Gabali (2009)** considers time-dependent travel times between the links, they address the vehicle routing problem from two extreme standpoints; one seeks to optimize exclusively on total travel time; the other does so on total CO_2 emissions. They also present a cost-based model that optimizes on a weighted average of travel time, emission and fuel costs.

Literature

* **Paksoy et al. (2011)** presented a multi-objective linear programming model of a closed-loop supply chain network that minimizes transportation, green and raw material purchasing costs. An interesting feature of this model formulation is that penalty costs are levied in the reverse logistics portion of the model for extra carbon dioxide emissions.

* **Bektas and Laporte (2011)** present the Pollution-Routing Problem, an extension of the classical Vehicle Routing Problem with a broader and more comprehensive objective function that accounts not just for the travel distance, but also for the amount of greenhouse emissions, fuel, travel times and their costs.

Contribution and aim of study

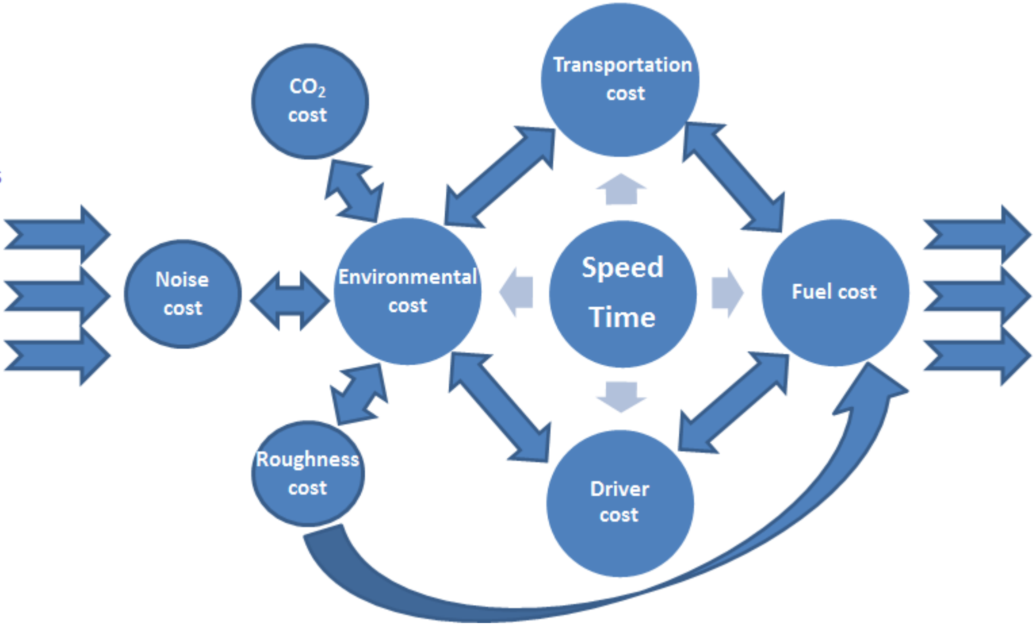
* This brief survey shows that most studies fail to properly integrate environmental factors, in particular, GHG emissions, and the more traditional operational and economic objectives in supply chain network problems.
* We note that few, if any, of the models incorporate green and/or sustainability variables directly or indirectly into their mathematical formulations.
* So, to the best of our knowledge, this paper suggests the first paper considering CO_2 emissions, fuel consumption, transportation speed/time, noise levels and road roughness factors in the context of supply chain network design based on mathematical formulation.

Decision model of the study

Decision Model

Decision Inputs

- Distance between facilities
- Transportation cost
- Noise cost
- Fuel cost
- CO_2 cost
- Capacities and demands
- Max and min speed levels
- Max noise levels



Decision Outputs

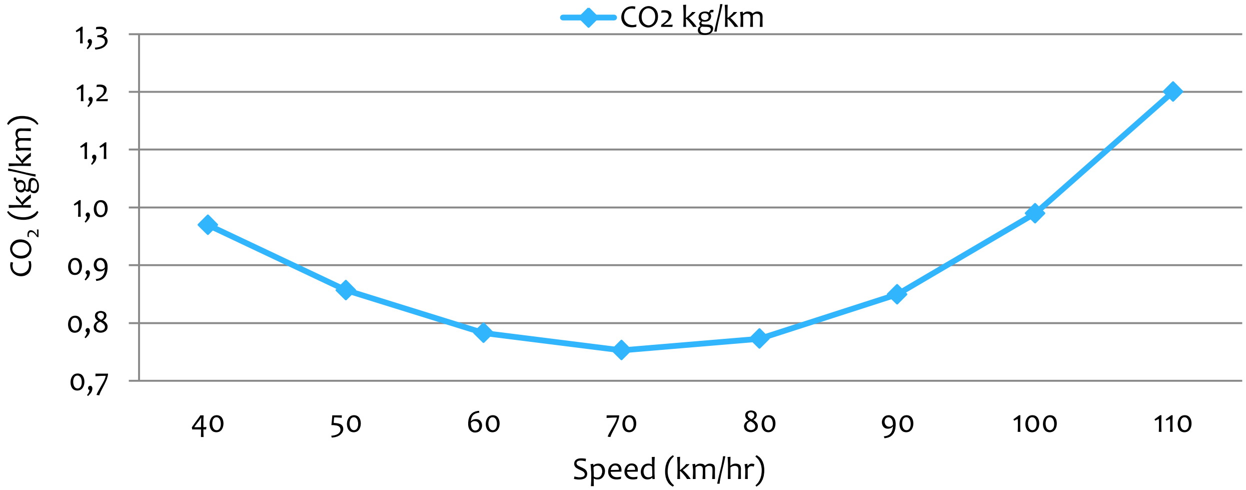
- Transported quantities and costs
- Transportation time and costs
- Transportation speed
- Emitted CO_2 and costs
- Emitted noise and costs
- Consumed fuel and costs

Problem Definition and Modeling

- In this model, we distinguish the costs and the time of shipments for satisfying the demands of customer, the costs in terms of gas emissions, as well as the costs in terms of other environmental factors,
- During the transportation it is certain that each vehicle emits a certain amount of greenhouse emissions.
- A speed emission function which is developed in the MEET report by European Commission (2009) is used in this study.
- The function $\theta(v)$ provides the emissions per km for speed v.
- Figure depicts emitted CO_2 amount versus speed this speed.

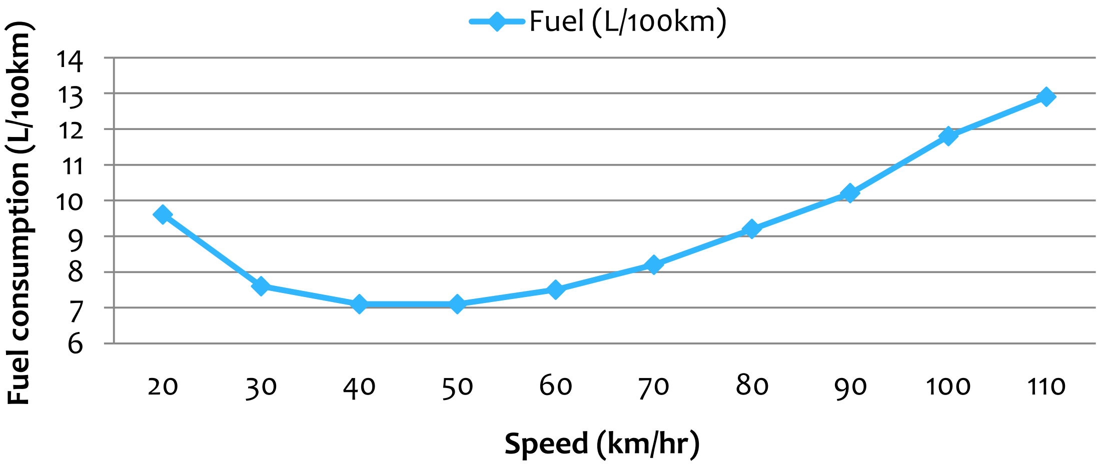
CO_2 Emission

- According to Figure, minimum CO_2 is emitted via a vehicle which has 71 km/hr. We defined 7 speed intervals and linear functions between 40 km/hr and 110 km/hr.
- Equation 1 depicts the amount of emissions emitted per km given that a vehicle is at speed v in speed interval *l*.
- $\theta_l(v) = a_l . v + b_l$ (1)



Fuel Consumption

* Besides the emissions factor, fuel consumption is also considered in this study.
* Fuel consumption is directly deal with speed of vehicle as CO_2 emission.
* Figure shows the relation consumed fuel (L/100km) amount and speed (km/hr) of vehicle **(Bektas and Laporte, 2011)**.



Fuel Consumption

* As it seen from the Figure, up to a certain level (50 km/hr), fuel consumption will decrease as speed increases.
* In contrast, after point 50 km/hr fuel consumption will increase with speed.
* Minimum fuel consumption is provided via a vehicle which has 40 and 50 km/hr.
* From the Figure, 7 different functions are obtained for each speed interval (Eq. 2).
* $\beta_l(v) = \hat{a}_l . v + \hat{b}_l$ (2)
* Where β_l is the consumed fuel amount (L/100 km) with speed v in speed interval l. The coefficients $(\hat{a}_l, \hat{b}_l)$ differ per speed intervals and given Table.

Coefficients of each speed interval functions for CO_2 emission and fuel consumptions

		CO_2 emissions		Fuel consumption	
No	Speed Intervals (km/hr)	a_l	b_l	$\hat{a}_l$	$\hat{b}_l$
l:1	40-50	−0.011274	1.42038	0	7.1
l:2	50-60	−0.007394	1.22638	0.04	5.1
l:3	60-70	−0.003007	0.96316	0.07	3.3
l:4	70-80	0.002001	0.61260	0.10	1.2
l:5	80-90	0.007670	0.15908	0.10	1.2
l:6	90-100	0.014023	−0.41269	0.16	− 4.2
l:7	100-110	0.021064	−1.11679	0.11	0.8

CO_2 emission

$$\theta_l(v) = a_l . v + b_l$$

$$\theta_l(55) = -0.007394 * 55 + 1.22638 \quad l = 2$$

$\theta_l(55)$=0.81971 kg/km

Fuel consumption

$$\beta_l(v) = \hat{a}_l . v + \hat{b}_l$$

$$\beta_l(55) = 0.04 * 55 + 5.1 \quad l = 2$$

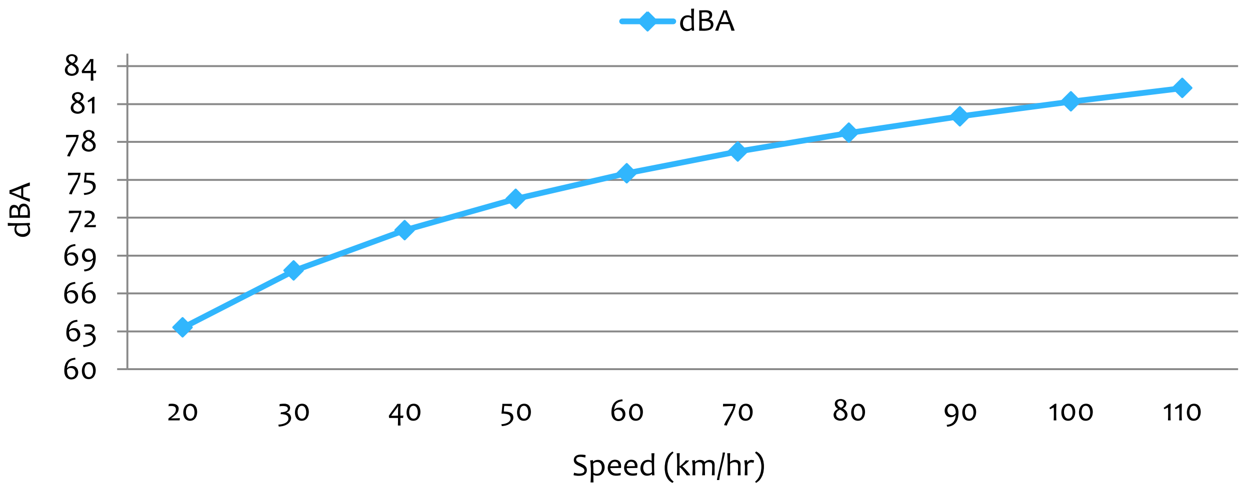
$\theta_l(55)$=7.3 L/100km

Noise factor

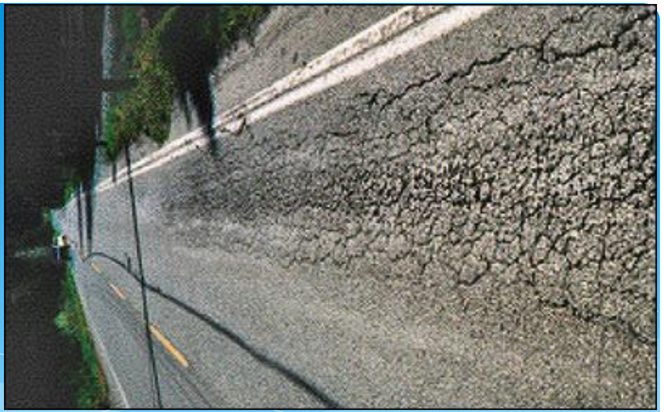
* Noise impact is handled under two situations.
* While the first one is in objective function which minimizes total noise cost produced by transportation in network, second one is get involved as a constraint in the model.
* Forkenbrock (1999) defines an approximate noise cost per freight truck mile is 0.58 cent, on an average ton-mile basis, the estimate is 0.04 cent.
* This cost is used in the proposed model as a penalty cost of noise pollution in the objective function.
* It is also known that transportation is a major source of noise pollution, which can be defined as unwanted or detrimental sound.
* The Federal Highway Administration (FHWA) has developed a simple noise emission model pertaining to trucks.
* The model takes into account the speed, number of axles, and weight of the truck to predict the peak noise level.

Noise factor

- Noise propagation models like the FHWA STAMINA model (FHWA, 1995) are applied to estimate noise levels at specified distances from a highway .
- The noise function related with vehicle speed is given below:
- $\alpha(v) = 30 + 26.5 \times Log_{10}(v)$ (3)
- Figure shows noise levels (dBA) obtained with average speed (km/hr) at 50 ft distances.



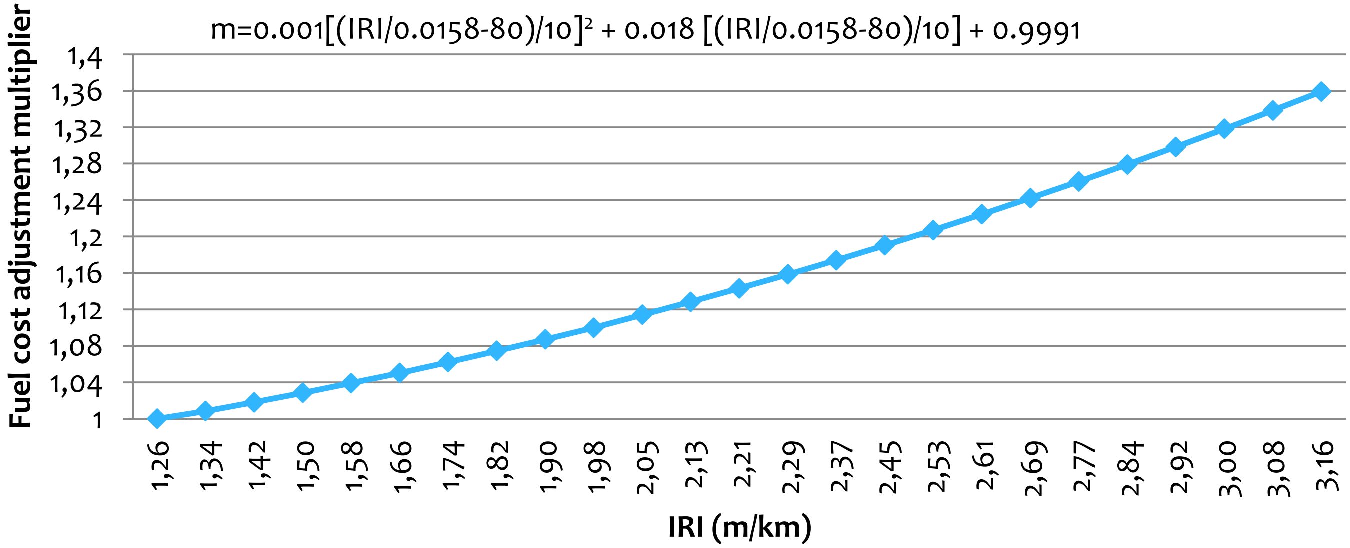
Road roughness factor



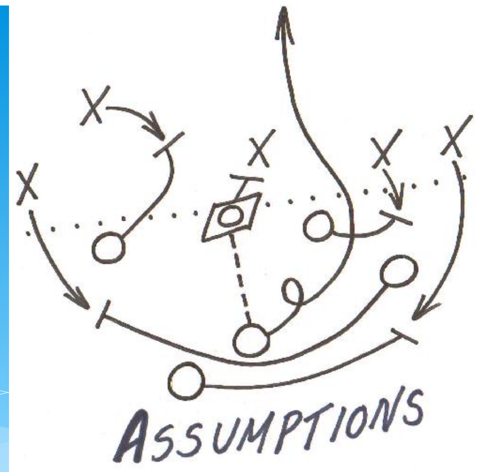
- Road roughness is another environmental factor often measured in terms of the international roughness index (IRI) which can affect the maintenance, tire, repair and depreciation cost components of transportation.
- This is because the motion of vehicle tires on a rough pavement surface is associated with greater resistance to movement, which can lead to higher levels of fuel consumption compared to transportation at a similar speed on a smooth surface.
- Also, an indirect effect of poor pavement conditions is that road users may be forced to drive at lower speeds, leading to higher fuel consumption.
- The relationship between pavement condition and transportation cost especially fuel cost has been conducted by Barnes and Langworthy (2003).

Road roughness factor

- They developed adjustment factors for all transportation cost components combined, as a function of pavement condition (Figure).
- They assumed a baseline IRI of 80 inch/mile or 1.26 m/km, at which further increases in pavement condition would have no impact on transportation costs.



Assumptions



* Further assumptions about the problem are stated below:
* The demand for each customer is for single-period, is deterministic and must be fully satisfied (i.e. no shortages are allowed).
* The demands and the transported materials are divisible amounts, which is applicable in the case of supply chains of gas or liquid products.
* The flow is only allowed to be transferred between two sequential echelons.
* The capacities suppliers and manufacturers are limited and are fixed.
* Transportation, noise, CO_2 emission, fuel costs and wages are deterministic.
* IRI of each road and permitted max noise levels are known.

Mathematical Formulation

Indices

i index of suppliers with $i=1, 2,..I$

j index of manufacturers with $j=1, 2,..J$

k index of customers with $k=1, 2,..K$

l index of speed intervals $l= 1, 2,..L$

Cost Parameters

C_t unit cost of transportation (except fuel and salary) per ton-km ($/ton*km)

C_n social cost of noise per ton-km of transportation ($/ton*km)

C_{co2} social cost of CO_2 emissions of transportation ($/kg)

C_f cost of one liter fuel oil ($/L)

C_{dr} hourly wage of driver ($/hour)

Mathematical Formulation

Other Parameters

d_{ij} distance between supplier *i* and manufacturer *j* (km)

d_{jk} distance between manufacturer *j* and customer *k* (km)

Ca_i capacity of supplier *i* (ton)

Ca_j capacity of manufacturer *j* (ton)

D_k demand of customer *k* (ton)

R_{ij} road roughness level between supplier *i* and manufacturer *j* (m/km)

R_{jk} road roughness level between manufacturer *j* and customer *k* (m/km)

Ad_{ij} fuel cost adjustment multiplier between supplier *i* and manufacturer *j*

Ad_{jk} fuel cost adjustment multiplier manufacturer *j* and customer *k*

dBA_{ij} permitted max noise level between supplier *i* and manufacturer *j* (dBA)

dBA_{jk} permitted max noise level between manufacturer *j* and customer *k* (dBA)

Min_l permitted min speed level in speed interval *l* (km/hour)

Max_l permitted max speed level in speed interval *l* (km/hour)

Mathematical Formulation

Variables

Q_{ij} amount of products transported from supplier *i* to manufacturer *j* (unit)

R_{jk} amount of products transported from manufacturer *j* to customer *k* (unit)

T_{ij} delivery time from supplier *i* to manufacturer *j* (hour)

B_{jk} delivery time from manufacturer *j* to customer *k* (hour)

E_{ij} exposed CO_2 emission between supplier *i* and manufacturer *j* (kg/km)

G_{jk} exposed CO_2 emission between manufacturer *j* and customer *k* (kg/km)

U_{ijl} speed of vehicle between supplier *i* and manufacturer *j* in speed interval *l* (km/hour)

H_{jkl} speed of vehicle between manufacturer *j* and customer *k* in speed interval *l* (km/hour)

Mathematical Formulation

Variables

F_{ij} consumed fuel oil between supplier *i* and manufacturer *j* (L/100 km)

S_{jk} consumed fuel oil between manufacturer *j* and customer *k* (L/100 km)

X_{ij} if transportation is actualized between supplier *i* and manufacturer *j*, 1; otherwise, 0

Y_{jk} if transportation is actualized between manufacturer *j* to customer *k*, 1; otherwise, 0

P_{ijl} if a vehicle moved between supplier *i* and manufacturer *j* in speed interval *l*, 1; otherwise, 0

D_{jkl} if a vehicle moved between manufacturer *j* and customer *k* in speed interval *l*, 1; otherwise, 0

Objective Function

$$\sum_i \sum_j Q_{ij}.\, d_{ij}.\, C_t + \sum_j \sum_k Q_{jk}.\, d_{jk}.\, C_t + \quad (4)$$
$$\sum_i \sum_j Q_{ij}.\, d_{ij}.\, C_n + \sum_j \sum_k Q_{jk}.\, d_{jk}.\, C_n + \quad (5)$$
$$\sum_i \sum_j E_{ij}\, .\, d_{ij}.\, C_{co2} + \sum_j \sum_k G_{jk}\, .\, d_{jk}.\, C_{co2} + \quad (6)$$
$$\sum_i \sum_j C_f.\, Ad_{ij}.\, F_{ij}\, .\, d_{ij}/100 + \sum_j \sum_k C_f.\, Ad_{jk}.\, S_{jk}\, .\, d_{jk}/100\ + \quad (7)$$
$$\sum_i \sum_j T_{ij}\, .\, C_{dr} + \sum_j \sum_k B_{jk}\, .\, C_{dr} \quad (8)$$

Component (4) represents the cost of transportation in both two echelons.

Component (5) measures total noise cost incurred by the loaded vehicle.

Component (6) represents total CO_2 emissions cost which is calculated θ_l function.

Component (7) measures total fuel consumption cost per 100 km via using β_l function.

Component (8) measures the total amount paid to drivers according to transportation time.

Constraints

$$\sum_j Q_{ij} \leq Ca_i \qquad \forall_i \qquad (9)$$

$$\sum_k R_{jk} \leq Ca_j \qquad \forall_j \qquad (10)$$

$$\sum_j R_{jk} \geq D_k \qquad \forall_k \qquad (11)$$

$$\sum_i Q_{ij} - \sum_k R_{jk} = 0 \qquad \forall_j \qquad (12)$$

$$Q_{ij} - M.X_{ij} \leq 0 \qquad \forall_{i,j} \qquad (13)$$

$$Q_{ij} - M.X_{ij} \geq 1 - M \qquad \forall_{i,j} \qquad (14)$$

$$R_{jk} - M.Y_{jk} \leq 0 \qquad \forall_{j,k} \qquad (15)$$

$$R_{jk} - M.Y_{jk} \geq 1 - M \qquad \forall_{j,k} \qquad (16)$$

Constraints

$$\sum_l P_{ijl} = X_{ij} \qquad \forall_{i,j} \qquad (17)$$

$$\sum_l D_{jkl} = Y_{jk} \qquad \forall_{j,k} \qquad (18)$$

$$U_{ijl}.T_{ij} = d_{ij}.P_{ijl} \qquad \forall_{i,j,l} \qquad (19)$$

$$H_{jkl}.B_{jk} = d_{ij}.D_{jkl} \qquad \forall_{j,k,l} \qquad (20)$$

$$30 + 25.6 \times Log10(U_{ijl}) \leq dBA_{ij} \qquad \forall_{i,j,l} \qquad (21)$$

$$30 + 25.6 \times Log10(H_{jkl}) \leq dBA_{jk} \qquad \forall_{j,k,l} \qquad (22)$$

$$P_{ijl}.Min_l \leq U_{ijl} \leq P_{ijl}.Max_l \qquad \forall_{i,j,l} \qquad (23)$$

$$D_{ijl}.Min_l \leq H_{jkl} \leq D_{ijl}.Max_l \qquad \forall_{j,k,l} \qquad (24)$$

Constraints

$$E_{ij} \geq \theta_l\left(U_{ijl}\right) - M \times (1 - P_{ijl}) \quad \forall_{i,j,l} \quad (25)$$

$$G_{jk} \geq \theta_l\left(H_{jkl}\right) - M \times (1 - D_{jkl}) \quad \forall_{j,k,l} \quad (26)$$

$$F_{ij} \geq \beta_l\left(U_{ijl}\right) - M \times (1 - P_{ijl}) \quad \forall_{i,j,l} \quad (27)$$

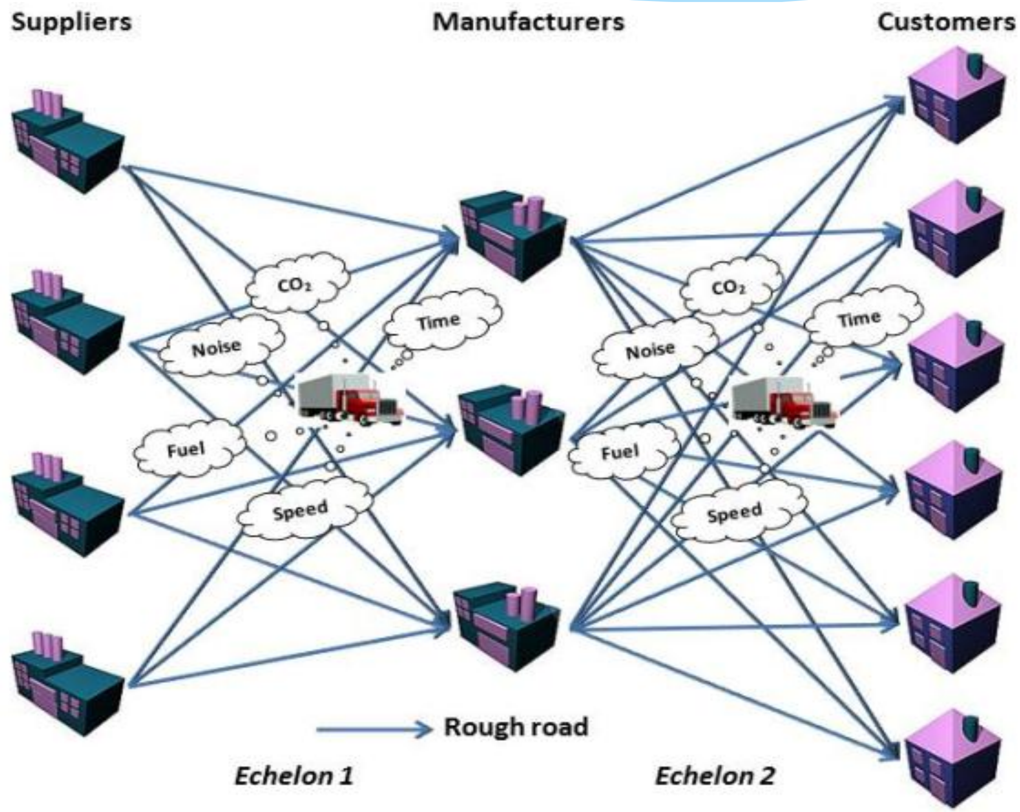
$$S_{jk} \geq \beta_l\left(H_{jkl}\right) - M \times (1 - D_{jkl}) \quad \forall_{j,k,l} \quad (28)$$

$$Q_{ij}, R_{jk}, E_{ij}, G_{jk}, T_{ij}, B_{jk}, F_{ij}, S_{jk}, U_{ijl}, H_{jkl} \geq 0 \quad \forall_{i,j,k,l} \quad (29)$$

$$X_{ij}, Y_{jk}, P_{ijl}, D_{jkl} = \{0,1\} \quad \forall_{i,j,k,l} \quad (30)$$

Numerical Example

We consider a two-echelon supply chain network in which the chain members are suppliers, manufacturers and customers, respectively.



Unit Costs

* Forkenbrock (1999, 2001) defines unit transportation cost as 8.42 cents per ton-mile (5.23 cents per ton-km) and fuel and wage cost is 27% of this cost according to their study.
* Thus, unit transportation cost (except fuel and driver wage) is given as 3.81 cents per ton-km in the example.
* 0.04 cents per ton-mile (0.025 cents per ton-km) is considered for noise cost (Forkenbrock 1999, 2001).
* The cost of fuel is set to 2.58$ per liter which is an average figure for Turkey (Opet, 2011).
* The cost of CO_2 emissions is calculated using the fact that one L of gasoline contains 2.32 kg of CO_2 (Bektas and Laporte, 2011). Therefore, it is accepted 1.11 $ per CO_2 kg.
* The hourly wage of a driver is set to an average figure of 12.85$ per hour.

Distances

Distance and roughness levels between suppliers and manufactures (km) / (m/km)

	Manufacturer 1	Manufacturer 2	Manufacturer 3
Supplier 1	164/2.53	353/1.58	106/2.69
Supplier 2	200/1.74	385/1.42	182/2.21
Supplier 3	74/3.08	197/2.05	209/1.90
Supplier 4	92/2.84	97/2.92	227/1.82

Distance and roughness levels between manufactures and customers (km) / (m/km

	Customer 1	Customer 2	Customer 3	Customer 4	Customer 5	Customer 6
Manufacturer 1	551/2.13	487/2.61	503/2.05	258/3.00	500/1.98	699/1.58
Manufacturer 2	490/2.45	691/1.50	462/2.37	320/2.77	196/3.08	490/2.21
Manufacturer 3	328/2.69	274/2.92	502/1.90	257/3.08	699/1.66	916/1.34

Noise levels, Capacities and Demands

(10 units=1 ton)

Permitted max noise levels between suppliers-manufacturers-customers (dBA)

	Manufacturers			Customers						
Suppliers	1	2	3	1	2	3	4	5	6	Manufacturers
1	81.1	81.3	82	81.7	81.4	82	81.6	81.7	81	1
2	80.9	81	81.2	81.3	81.7	82.1	81.3	82	81.3	2
3	82	81	80.5	81.8	81.7	81.5	81.7	81.9	81.4	3
4	81.5	80.2	81	-	-	-	-	-	-	

Capacities of suppliers and manufacturers, and demands of customers

	1	2	3	4	5	6
Suppliers	2100	2300	2000	1900	-	-
Manufacturers	2100	1700	1800	-	-	-
Customers	900	950	900	850	950	900

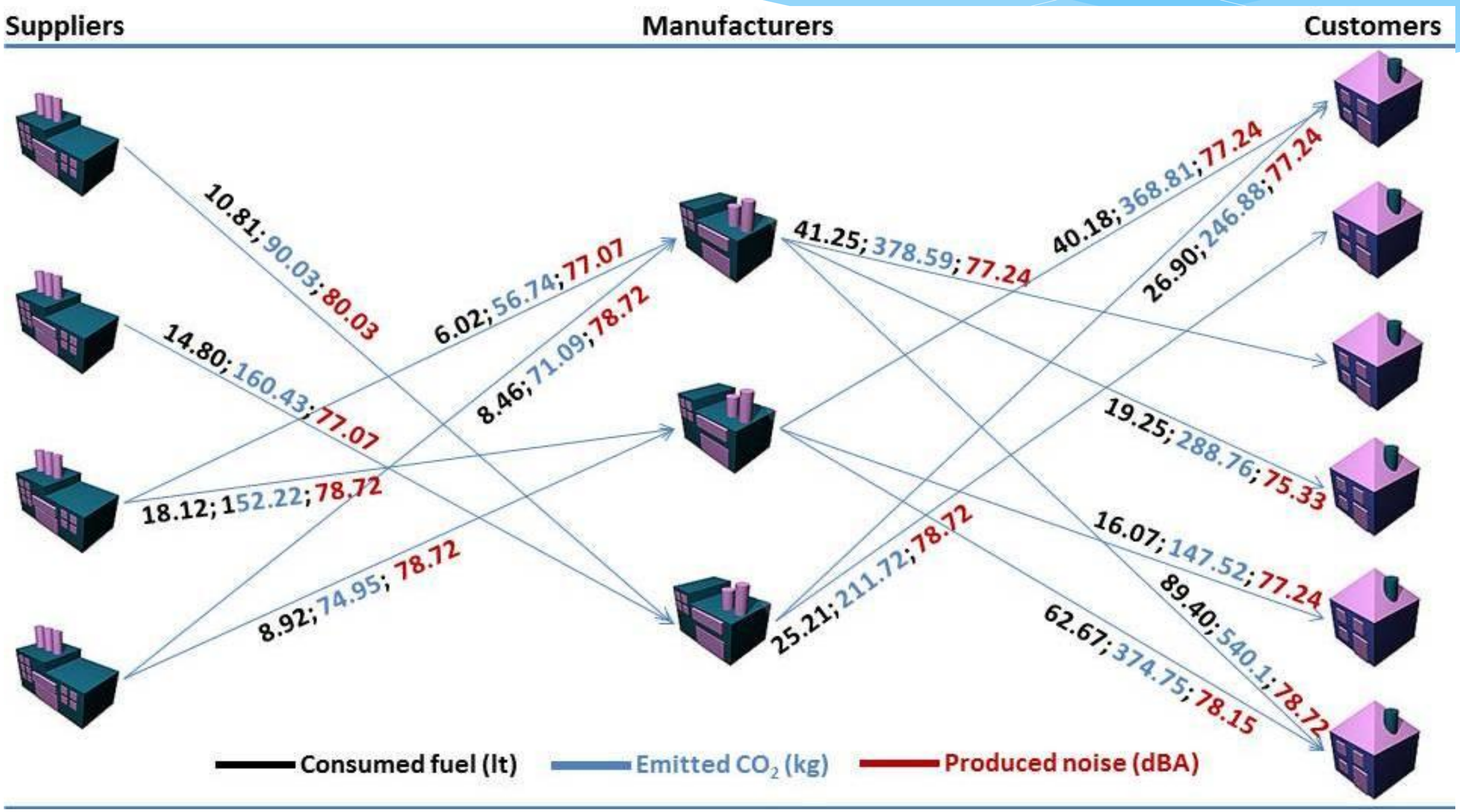
Solution

* The nonlinear programming formulation (1)-(30) of the sample network contains 582 variables and 1497 constraints.
* Computational experiment is conducted on a notebook with Intel Core2 Duo 1.66 GHz and 2 GB RAM and the required computation time to solve the model to optimality using LINGO 11.0 is 43 seconds.

Variable	Value	Variable	Value	Variable	Value	Variable	Value	Variable	Value	Variable	Value
Q_{13}	1000	E_{32}	0.77268	S_{13}	8.20	B_{21}	7.00	H_{314}	70	X_{23}	1
Q_{23}	800	E_{41}	0.77268	S_{14}	7.46	B_{25}	2.80	H_{325}	80	X_{31}	1
Q_{31}	1000	E_{42}	0.77268	S_{16}	12.79	B_{26}	6.44	P_{136}	1	X_{32}	1
Q_{32}	750	G_{13}	0.75267	S_{21}	8.20	B_{31}	4.69	P_{233}	1	X_{41}	1
Q_{41}	950	G_{14}	1.11922	S_{25}	8.20	B_{32}	3.43	P_{313}	1	X_{42}	1
Q_{42}	950	G_{16}	0.77268	S_{26}	12.79	U_{136}	90	P_{325}	1	Y_{13}	1
R_{13}	900	G_{21}	0.75267	S_{31}	8.20	U_{233}	69	P_{415}	1	Y_{14}	1
R_{14}	850	G_{25}	0.75267	S_{32}	9.20	U_{313}	69	P_{425}	1	Y_{16}	1
R_{16}	200	G_{26}	0.76480	T_{13}	1.18	U_{325}	80	D_{134}	1	Y_{21}	1
R_{21}	50	G_{31}	0.75267	T_{23}	2.64	U_{415}	80	D_{142}	1	Y_{25}	1
R_{25}	950	G_{32}	0.77268	T_{31}	1.07	U_{425}	80	D_{165}	1	Y_{26}	1
R_{26}	700	F_{13}	10.20	T_{32}	2.46	H_{134}	70	D_{214}	1	Y_{31}	1
R_{31}	850	F_{23}	8.13	T_{41}	1.15	H_{142}	59	D_{254}	1	Y_{32}	1
R_{32}	950	F_{31}	8.13	T_{42}	1.21	H_{165}	80	D_{264}	1		
E_{13}	0.84938	F_{32}	9.20	B_{13}	7.19	H_{214}	70	D_{314}	1		
E_{23}	0.88149	F_{41}	9.20	B_{14}	4.37	H_{254}	70	D_{325}	1		
E_{31}	0.76669	F_{42}	9.20	B_{16}	8.74	H_{264}	76	X_{13}	1		

Optimal flow through the chain

Consumed fuel amounts, emitted CO_2 emissions and produce noise levels between facilities in the optimal solution



Optimal Costs

	Performance Criteria	Value ($)	% of the total cost
PC1	Total objective function value	14759.56	100.00
PC2	Total transportation costs	9744.08	66.02
PC3	Total transportation cost in first echelon	2487.55	16.85
PC4	Total transportation cost in second echelon	7256.53	49.17
PC5	Total fuel costs	742.52	5.04
PC6	Total fuel cost in first echelon	208.98	1.42
PC7	Total fuel cost in second echelon	533.54	3.62
PC8	Total driver costs	698.55	4.74
PC9	Total driver cost in first echelon	124.81	0.85
PC10	Total driver cost in second echelon	573.74	3.89
PC11	Total environmental costs	3574.41	24.20
PC12	Total CO_2 emission cost in first echelon	672.06	4.55
PC13	Total CO_2 emission cost in second echelon	2838.41	19.23
PC14	Total noise cost in first echelon	16.32	0.11
PC15	Total noise cost in second echelon	47.62	0.31

Scenario Analyses for Managerial Insights

* A number of instances are generated to carry out scenario analyses in which problem parameters are changed to see the effect on the performance measures (especially PC1-PC2-PC5-PC8-PC11) stated below.

	Performance Criteria
PC1	Total objective function value
PC2	Total transportation costs
PC5	Total fuel costs
PC8	Total driver costs
PC11	Total environmental costs

Scenarious

Effect of changing demands (Scenario 1)

Effect of changing suppliers' capacity (Scenario 2)

Effect of changing manufacturers' capacity (Scenario 3)

Effect of changing suppliers' and manufacturers' capacity simultaneously (Scenario 4)

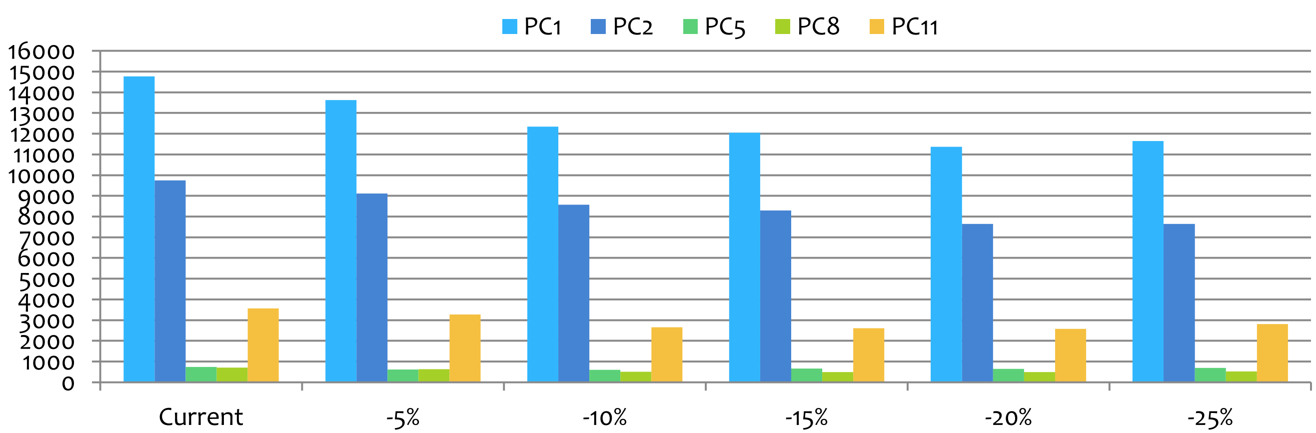
Effect of changing demands (Scenario 1)

Performance measures as a fraction of total cost under changing demands

Set 1	PC1 ($)	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15
Current	14759.56	66.02	16.85	49.17	5.04	1.42	3.62	4.74	0.85	3.89	24.20	4.55	19.23	0.11	0.31
-5%	13624.76	66.89	17.30	49.59	4.50	1.44	3.06	4.60	0.98	3.62	24.01	4.81	18.75	0.12	0.33
-10%	12345.05	69.48	17.96	51.52	4.91	1.63	3.28	4.14	1.06	3.08	21.47	5.17	15.84	0.12	0.33
-15%	12050.56	68.76	18.93	49.83	5.45	1.99	3.46	4.12	1.11	3.01	21.66	6.06	15.15	0.12	0.33
-20%	11365.47	67.32	17.58	49.74	5.62	1.95	3.67	4.34	1.24	3.19	22.64	6.13	16.06	0.12	0.33
-25%	11653.49	65.53	20.06	45.47	5.89	2.24	3.65	4.52	1.44	3.08	24.08	7.79	15.86	0.13	0.30

Performance values for Scenario 2 (Ech: echelon)

	Travelled Distance (km)		Average transportation time (hour)		Average transportation speed (km/hour)		Consumed Fuel (lt)		Emitted CO_2 (kg)		Average produced noise (dBA)	
Set 1	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2
Current	748	3238	1.62	5.58	78.00	71.86	81.00	206.80	605.46	2557.13	78.39	77.49
-5%	748	2748	1.73	5.48	73.17	72.00	76.30	161.61	590.41	2322.53	77.72	77.55
-10%	748	2049	1.70	4.93	75.00	70.83	77.84	157.18	575.19	1762.15	77.95	77.32
-15%	838	2049	1.74	4.70	80.00	72.50	92.87	161.61	658.24	1644.78	78.69	77.61
-20%	820	2049	1.82	4.70	74.67	72.50	85.79	161.61	627.37	1644.78	77.93	77.61
-25%	1004	2049	2.17	4.66	76.33	74.17	101.12	164.65	817.66	1664.71	78.15	77.83



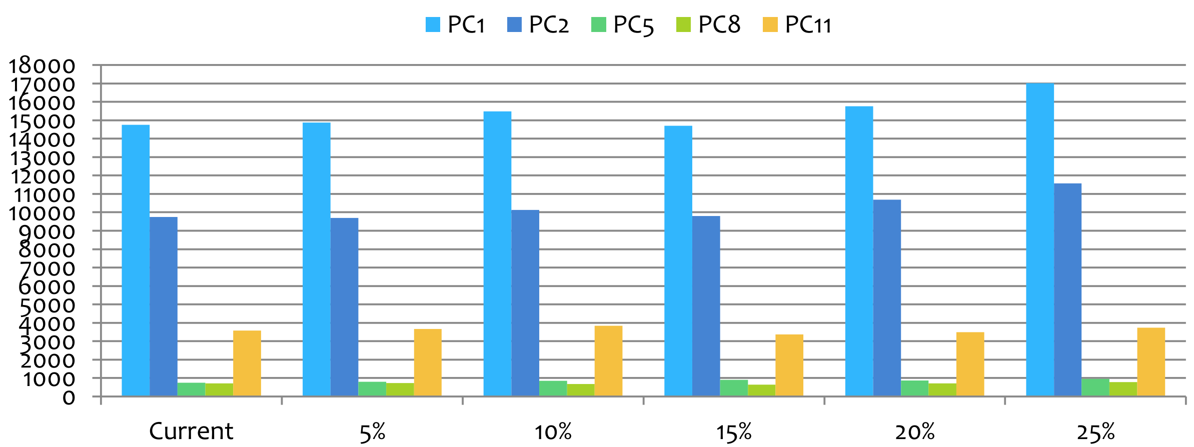
Effect of changing suppliers' capacity (Scenario 2)

Performance measures as a fraction of total cost under changing suppliers' capacity

Set 2	PC1 ($)	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15
Current	14759.56	66.02	16.85	49.17	5.04	1.42	3.62	4.74	0.85	3.89	24.20	4.55	19.23	0.11	0.31
+5%	14878.77	65.16	16.59	48.57	5.32	1.63	3.69	4.89	1.08	3.81	24.63	5.21	18.99	0.11	0.32
+10%	15476.33	65.47	18.32	47.15	5.46	1.60	3.86	4.32	0.95	3.37	24.76	5.20	19.13	0.12	0.31
+15%	14707.13	66.61	16.78	49.83	6.17	1.29	4.88	4.36	0.94	3.42	22.86	4.26	18.16	0.11	0.33
+20%	15760.90	67.83	17.28	50.55	5.49	1.35	4.14	4.51	0.93	3.58	22.17	4.38	17.35	0.11	0.33
+25%	17017.90	67.96	24.89	43.07	5.56	1.77	3.79	4.55	1.25	3.30	21.94	6.30	15.20	0.16	0.28

Performance values for Scenario 2

	Travelled Distance (km)		Average transportation time (hour)		Average transportation speed (km/hour)		Consumed Fuel (lt)		Emitted CO_2 (kg)		Average produced noise (dBA)	
Set 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2
Current	748	3238	1.62	5.58	78.00	71.86	81.00	206.80	605.46	2557.13	78.39	77.49
+5%	912	3235	1.79	5.52	74.29	73.88	94.08	212.59	698.63	2545.44	77.85	77.82
+10%	904	3238	1.91	5.07	76.67	80.62	96.00	231.47	724.80	2667.45	78.17	78.75
+15%	748	3039	1.79	4.90	69.67	79.25	73.72	278.11	563.84	2405.91	77.19	78.57
+20%	820	3068	1.90	5.49	71.50	73.50	82.64	252.99	621.42	2463.49	77.46	77.70
+25%	1224	3039	2.76	5.46	73.17	69.63	116.83	250.24	965.30	2329.56	77.71	77.18



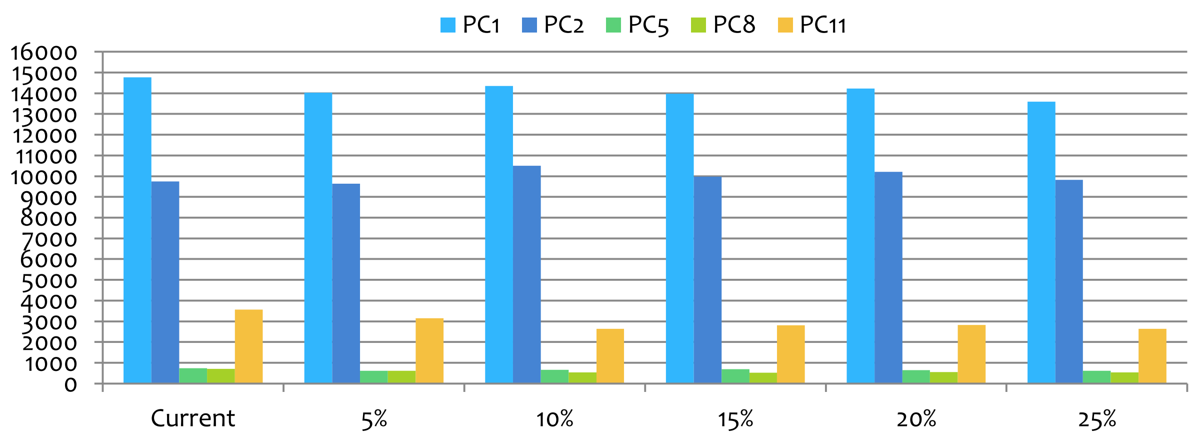
Effect of changing manufacturers' capacity (Scenario 3)

Performance measures as a fraction of total cost under changing manufacturers' capacity

Set 3	PC1 ($)	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15
Current	14759.56	66.02	16.85	49.17	5.04	1.42	3.62	4.74	0.85	3.89	24.20	4.55	19.23	0.11	0.31
+5%	14019.50	68.74	17.97	50.77	4.34	1.38	2.96	4.42	0.97	3.45	22.50	4.49	17.56	0.12	0.33
+10%	14347.89	73.17	23.92	49.25	4.65	1.74	2.91	3.76	1.24	2.52	18.42	5.91	12.03	0.16	0.32
+15%	13986.46	71.31	20.79	50.52	4.90	1.93	2.97	3.76	1.15	2.61	20.04	6.21	13.36	0.14	0.33
+20%	14224.80	71.74	22.06	49.68	4.58	1.76	2.82	3.83	1.11	2.72	19.87	6.28	13.11	0.15	0.33
+25%	13589.92	72.25	20.25	52.00	4.47	1.53	2.94	3.93	1.13	2.80	19.37	5.11	13.79	0.13	0.34

Performance values for Scenario 3

	Travelled Distance (km)		Average transportation time (hour)		Average transportation speed (km/hour)		Consumed Fuel (lt)		Emitted CO_2 (kg)		Average produced noise (dBA)	
Set 3	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2
Current	748	3238	1.62	5.58	78.00	71.86	81.00	206.80	605.46	2557.13	78.39	77.49
+5%	748	2748	1.77	5.37	71.17	72.71	74.91	160.67	566.85	2218.09	77.41	77.64
+10%	1004	2049	2.31	4.69	73.00	72.67	97.00	162.00	763.33	1554.73	77.68	77.64
+15%	975	2049	1.79	4.73	81.29	72.33	104.68	160.86	782.23	1682.91	78.79	77.59
+20%	931	2049	2.06	5.01	81.33	67.67	96.89	155.36	804.09	1680.30	78.78	76.84
+25%	820	2049	1.99	4.93	69.17	68.83	80.41	154.67	625.62	1703.03	77.06	77.02



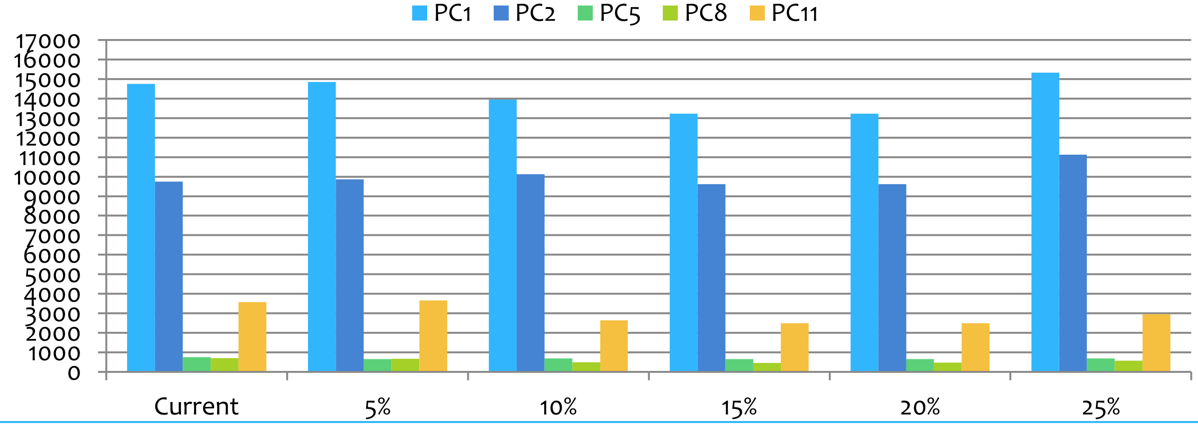
Effect of changing suppliers' and manufacturers' capacity simultaneously (Scenario 4)

Performance measures as a fraction of total cost under changing suppliers' and manufacturers' capacity

Set 4	PC1 ($)	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9	PC10	PC11	PC12	PC13	PC14	PC15
Current	14759.56	66.02	16.85	49.17	5.04	1.42	3.62	4.74	0.85	3.89	24.20	4.55	19.23	0.11	0.31
+5%	14847.82	66.42	18.48	47.94	4.39	1.46	2.93	4.52	0.97	3.55	24.67	4.75	19.48	0.12	0.32
+10%	13942.83	72.56	21.88	50.68	4.95	1.70	3.25	3.51	1.10	2.41	18.96	5.69	12.80	0.14	0.33
+15%	13223.66	72.69	19.25	53.44	4.99	1.54	3.45	3.50	0.97	2.53	18.83	4.85	13.50	0.13	0.35
+20%	13224.38	72.69	19.25	53.44	4.98	1.53	3.45	3.51	0.98	2.53	18.83	4.85	13.50	0.13	0.35
+25%	15333.96	72.54	26.46	46.08	4.48	1.83	2.65	3.75	1.33	2.42	19.22	6.61	12.14	0.17	0.30

Performance values for Scenario 4

	Travelled Distance (km)		Average transportation time (hour)		Average transportation speed (km/hour)		Consumed Fuel (lt)		Emitted CO_2 (kg)		Average produced noise (dBA)	
Set 4	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2	Ech. 1	Ech. 2
Current	748	3238	1.62	5.58	78.00	71.86	81.00	206.80	605.46	2557.13	78.39	77.49
+5%	820	2748	1.88	5.87	73.00	70.86	84.27	168.70	640.45	2629.43	77.65	77.26
+10%	904	2049	1.99	4.36	74.83	77.67	92.13	175.83	714.99	1607.30	77.95	78.35
+15%	748	2049	1.67	4.35	75.00	77.67	78.78	176.61	577.19	1623.16	77.95	78.35
+20%	748	2049	1.67	4.35	74.83	77.67	78.63	176.61	577.74	1608.54	77.93	78.35
+25%	1152	2049	2.65	4.81	74.67	70.67	108.78	157.30	913.74	1677.43	77.90	77.34



Conclusion

* In this study a supply chain network design problem is modeled with consideration the trade-offs between operational and environmental factors of transporting products under capacities and demands constraints.
* A nonlinear integer programming approach is adapted to the proposed problem.
* The contributions of this paper were: (i) to describe a modeling approach for incorporating fuel consumption, CO_2 emission, noise level, and roughness factor into existing network planning methods for supply chains, (ii) to offer a novel nonlinear programming model for the network design problem which, in contrast to most of the existing studies, minimizes a total cost function composed of driver wage, fuel, noise, transportation, green gas emissions costs expressed as a function speed under roughness factor, (iii) to present extensive computational analyses that capture the trade-off between various performance measures.

Suggestions

Several additions could be embedded to the model;

- Different vehicles may yield more options for decision makers to optimize fuel consumption, CO_2 emission and total cost.
- Another extension should be to consider delivery time restrictions which may make the problem more realistic.
- Finally, more environmental factors such as road angle and accident risks and more facilities such as distribution centers, retailers or recycling activities should be embedded to model.
- At this time, using various simulation techniques or heuristics, such as, simulated annealing, tabu search, genetic algorithms will be mandatory due to being NP-complete of large sized models.

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Merci

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Salamat

Thank You

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Shoukran

ευχαριστία

Danke

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